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# Theory and phenomenology of lepton flavor violation

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The field of lepton flavor violation will live an era of unprecedented developments in the near future, with dedicated experiments in different fronts. The observation of a flavor violating process involving charged leptons would be a clear evidence of physics beyond the Standard Model, thus motivating the great effort in this direction. Furthermore, in case a positive signal is found, a proper theoretical understanding of the lepton flavor anatomy of a given model would become necessary. Here I briefly review the current situation, emphasizing the most relevant theoretical and phenomenological aspects of several processes. Finally, I discuss two topics that have received some attention recently: lepton flavor violation in low-scale seesaw models and lepton flavor violating Higgs decays.

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# 1 Introduction

The field of lepton flavor violation (LFV) is about to begin a golden era, with great expectations in several experimental projects \*. In the coming years, many collaborations will join the search for LFV, currently led by the popular MEG experiment. These new experiments will look for LFV in channels that not only include radiative lepton decays, but also 3-body lepton decays (such as  $\mu \rightarrow 3e$ ),  $\mu - e$  conversion in nuclei or LFV in high-energy colliders. With these great perspectives, we may be able to extend our knowledge on the physics beyond the Standard Model (SM) or, at least, to significantly improve the current bounds.

On general grounds, one expects large LFV effects if new physics exists close to the electroweak scale. In fact, most popular models predict large LFV rates. This is easily understood by simple considerations based on effective field theory. Let us consider the dim-6 operator

$$\mathcal{O}_{e\mu} = \frac{c_{e\mu}}{\Lambda^2} \bar{\mu} e \bar{e} e, \quad (1)$$

induced by some heavy degrees of freedom with masses of the order of  $\Lambda$ . It violates the electron and muon flavors, thus inducing processes such as  $\mu \rightarrow 3e$ . Using the current bounds on this process one finds that the condition  $\Lambda/\sqrt{c_{e\mu}} > 100$  TeV must be satisfied. Therefore, if new physics capable of inducing the operator  $\mathcal{O}_{e\mu}$  is found at the TeV scale, some suppression mechanism must be introduced in order to satisfy the current LFV bounds. This, together with the promising experimental perspectives, makes LFV an interesting road in the search for new physics, complementary to the direct path based on high-energy colliders.

In case a positive observation in one or several experiments is made, the correct interpretation of the results in a given model will definitely require a detailed understanding of its LFV anatomy. This theoretical effort should be ambitious. In addition to detailed computations, patterns and correlations must be properly identified in order to be able to extract as much information as possible. Only by combining these *tests*, typically valid for general classes of models, one can investigate the physics responsible for LFV.

An example of one of these patterns is the so-called *dipole dominance*. In many popular models, the operators with the dominant contributions to LFV processes are dipole operators induced by photon exchange. This is for example the case of the Minimal Supersymmetric Standard Model (MSSM). In this type of scenarios there is a very strong correlation between radiative lepton decays and the corresponding

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\*See Section 1 of Ref. [1] and references therein for a complete review of the current experimental situation and the future prospects.

3-body lepton decays,

$$\frac{\text{BR}(\ell_i \rightarrow 3 \ell_j)}{\text{BR}(\ell_i \rightarrow \ell_j \gamma)} = \frac{\alpha}{3\pi} \left( \log \frac{m_{\ell_i}^2}{m_{\ell_j}^2} - \frac{11}{4} \right), \quad (2)$$

which allow to obtain a clear hierarchy between LFV observables,  $\text{BR}(\ell_i \rightarrow \ell_j \gamma) \gg \text{BR}(\ell_i \rightarrow 3 \ell_j)$ . An analogous relation can be found for other LFV processes, like  $\mu - e$  conversion in nuclei, that are also suppressed with respect to the radiative muon decay. The violation of these hierarchies would be a clear signal of a departure from these standard scenarios, and thus they should be considered as powerful experimental tests.

In the following we are going to discuss two specific topics: LFV in low-scale seesaw models and Higgs LFV decays.

## 2 LFV in low-scale seesaw models

Low-scale seesaw models offer an interesting alternative to the usual high-energy realizations of the seesaw mechanism. Instead of a large mass scale, low-scale seesaw models rely on the violation of lepton number by a small parameter. This allows one to explain the smallness of neutrino masses and, simultaneously, have right-handed (RH) neutrinos at the TeV scale (or below), thus contributing to LFV processes.

In the Inverse Seesaw [2], the SM particle content is extended by  $n_R$  generations of RH neutrinos  $\nu_R$  and  $n_X$  generations of singlet fermions  $X$ , both with lepton number  $L = +1$ . In the following we will assume  $n_R = n_X = 3$ , although more minimal models are also possible [3]. The Lagrangian has the form

$$\mathcal{L}_{\text{ISS}} = \mathcal{L}_{\text{SM}} - Y_{\nu}^{ij} \overline{\nu_{Ri}} \tilde{H}^{\dagger} L_j - M_R^{ij} \overline{\nu_{Ri}} X_j - \frac{1}{2} \mu_X^{ij} \overline{X_i^C} X_j + h.c., \quad (3)$$

where a sum over  $i, j = 1, 2, 3$  is assumed. Here  $\mathcal{L}_{\text{SM}}$  is the SM Lagrangian,  $Y_{\nu}$  are the neutrino Yukawa couplings,  $M_R$  is a complex Dirac mass matrix for the fermion singlets and  $\mu_X$  is a complex symmetric Majorana mass matrix that violates lepton number by two units. The supersymmetric (SUSY) extension of this model is simply obtained by promoting all fields to superfields. Furthermore, we note that  $\mu_X$  is naturally small, in the sense of 't Hooft [4], since in the limit  $\mu_X \rightarrow 0$  lepton number is restored.

After electroweak symmetry breaking, in the basis  $(\nu_L, \nu_R^C, X)$ , the  $9 \times 9$  neutrino mass matrix is given by

$$M_{\text{ISS}} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}. \quad (4)$$

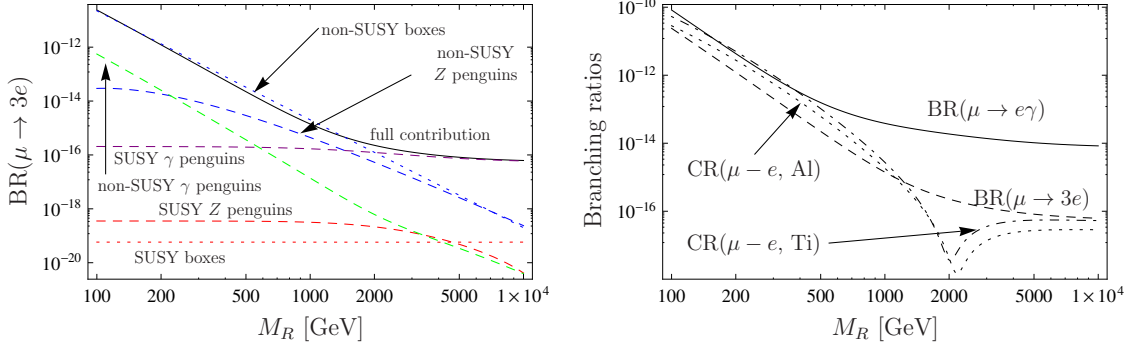


Figure 1: On the left-hand side,  $\text{BR}(\mu \rightarrow 3e)$  as a function of  $M_R$ . The continuous black line represents the total branching ratio, whereas individual contributions are shown with dashed lines. On the right-hand side,  $\text{BR}(\mu \rightarrow e\gamma)$ ,  $\text{BR}(\mu \rightarrow 3e)$ ,  $\mu - e$  conversion rates in Ti and Al as a function of  $M_R$ . Figure from [1].

where  $m_D = \frac{1}{\sqrt{2}}Y_\nu v$  and  $v/\sqrt{2}$  is the vacuum expectation value (VEV) of the Higgs field. Under the assumption  $\mu_X \ll m_D \ll M_R$ , the mass matrix  $M_{\text{ISS}}$  can be block-diagonalized to give the effective mass matrix for the light neutrinos  $m_{\text{light}} \simeq m_D^T M_R^{-1} \mu_X M_R^{-1} m_D$ , whereas the heavy quasi-Dirac neutrinos have masses corresponding approximately to the entries of  $M_R$ . Since the light neutrino masses are proportional to  $\mu_X$ , the smallness of this parameter can be used to accommodate the values measured in neutrino oscillation experiments while having  $M_R \sim \text{TeV}$ . This has important consequences for LFV.

Early works on LFV in models with light RH neutrinos [5, 6, 7, 8] already pointed out the existence of large enhancements in the LFV rates with respect to those found in high-scale models. More recently, dominant RH neutrino contributions have been found in box diagrams [9, 10, 11, 12], as well as in the usual photon penguin diagrams [13]. Finally, the first complete LFV study including all contributions in the non-supersymmetric as well as in the supersymmetric version of the inverse see-saw was presented in [1]. The calculation of the LFV observables was done with **FlavorKit** [14], a computer tool that allows for an automatized analytical and numerical computation of flavor observables. Thanks to this tool, it was possible to evaluate several hundreds of Feynman diagrams and obtain complete expressions for the LFV observables of interest.

As discussed in Sec. 1, many popular models have a dipole dominated LFV phenomenology. In this case, one expects specific hierarchies among LFV observables. In contrast, in the presence of light RH neutrinos the dipole dominance is broken. This is shown in Fig. 1, obtained from Ref. [1]. On the left, individual contributions to  $\text{BR}(\mu \rightarrow 3e)$  are shown as a function of  $M_R$ . Regarding the supersymmetric param-

eters, they were obtained at low energies using renormalization group running from the grand unification scale, where universal (and flavor-blind) CMSSM-like boundary conditions were imposed. All universal SUSY breaking parameters ( $m_0$ ,  $M_{1/2}$  and  $A_0$ ) were fixed to 1 TeV. One finds that for low  $M_R$  the non-SUSY contributions induced by the RH neutrinos dominate the total branching ratio. In particular, the non-SUSY boxes, as well as the non-SUSY  $\gamma$ - and  $Z$ -penguins, give the largest contributions. This confirms some partial results in previous works. The same choice of parameters was made on the right-side of Fig. 1, where several LFV observables are shown. As expected, for low  $M_R$  they can have similar rates, thus breaking the usual hierarchies found for the dipole dominance scenario.

### 3 Higgs LFV decays

The long-awaited discovery of the Higgs boson should not be seen as the end of the way, but as the beginning of an era in particle physics. A new particle always implies new measurements, and the Higgs boson properties and decay modes might hide very valuable information. Currently, the open question is whether the discovered state corresponds to the *standard* Higgs boson. If this is not the case, and a deviation from the SM expectation is found, we may be able to get a hint about new physics not far from the electroweak scale.

Recently, the possibility of LFV Higgs decays [15, 16] has attracted some attention. In addition to model independent studies on LFV Higgs couplings and their phenomenological impact [17, 18, 19, 20], several groups have searched for specific models capable of producing sizeable LFV Higgs decays with observable rates at the LHC. With  $\sqrt{s} = 8$  TeV and  $20 \text{ fb}^{-1}$ , the LHC is estimated to be sensitive to  $\text{BR}(h \rightarrow \ell_i \ell_j) \gtrsim 10^{-3}$  [21], which implies a very strong requirement on a model that aims at observable LFV Higgs decays. In fact, most models fail, as those large LFV Higgs rates would be in conflict with bounds from radiative lepton decays ( $\ell_i \rightarrow \ell_j \gamma$ ).

Let us consider an example. In [22], a generic model with additional vector-like leptons was investigated. The relevant Lagrangian terms are given by

$$\mathcal{L}_{F,c} = -M \left( \bar{L} C_L L + \bar{\tilde{E}} C_R \tilde{E} \right) - \left( \bar{L}_L Y \tilde{E}_R H + \bar{L}_R \tilde{Y} \tilde{E}_L H + \text{h.c.} \right), \quad (5)$$

$$\mathcal{L}_{\text{mix}} = M \left( \bar{l}_L \lambda_l L_R + \bar{\tilde{E}}_L \lambda_e e_R \right) + \text{h.c.} . \quad (6)$$

Here we have introduced the usual 3 generations of chiral leptons,  $l_L^i = (\nu_L^i, e_L^i)$ ,  $e_R^i$ ,  $i = 1 \dots 3$ , and 3 generations of vector-like leptons  $L^i = (N^i, E^i)$ ,  $\tilde{E}^i$ , transforming as  $2_{-1/2}$  and  $1_{-1}$  under the electroweak gauge group.  $C_L$ ,  $C_R$ ,  $Y$ ,  $\tilde{Y}$  and  $\lambda_i$  are  $3 \times 3$  matrices in generation space and a common scale  $M$ , the vector-like mass, has been isolated. The mixing between the SM leptons and the exotic states, together

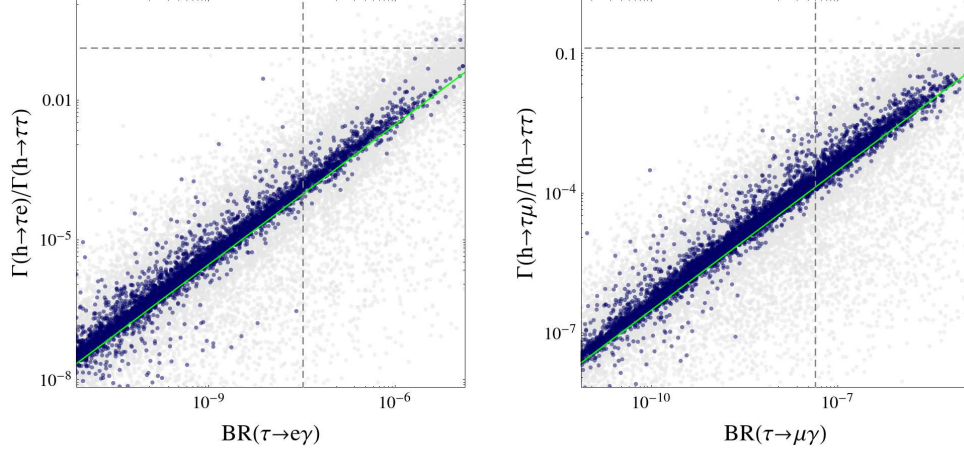


Figure 2: Correlation between LFV Higgs decays and radiative lepton decays. Gray points are ruled out by LHC direct searches. The experimentally allowed region is left of and below the dashed lines. Figure from [22].

with the coupling between the exotic leptons and the Higgs boson, leads to effective off-diagonal Higgs couplings to a pair of charged leptons,

$$\mathcal{L}_{\text{eff}} = -\frac{h}{\sqrt{2}}\bar{e}_L c_{\text{eff}} e_R + \text{h.c.} \quad c_{\text{eff}} = Y_{\text{eff}} + \frac{v^2}{M^2}\lambda_l C_L^{-1} Y C_R^{-1} \tilde{Y} C_L^{-1} Y C_R^{-1} \lambda_e, \quad (7)$$

where  $Y_{\text{eff}}$  is flavor diagonal. However, the same effective couplings,  $c_{\text{eff}}$ , contribute to radiative lepton decays, giving rise to a strong correlation between  $\text{BR}(h \rightarrow \ell_i \ell_j)$  and  $\text{BR}(\ell_i \rightarrow \ell_j \gamma)$ . This is shown in Fig. 2. When the current bounds on  $\text{BR}(\tau \rightarrow e \gamma)$  and  $\text{BR}(\tau \rightarrow \mu \gamma)$  are used, this correlation translates into Higgs LFV branching ratios below  $10^{-5}$ , below the LHC reach.

Similar perspectives are found in other scenarios [23, 24, 25]. In contrast, as a positive note, models with extended scalar sectors can in principle lead to observable LHV Higgs decays. The simplest of these frameworks is the Type-III Two Higgs Doublet Model (2HDM)<sup>†</sup>. Already suggested in previous works [30, 19, 31], this has been recently shown explicitly in [32], where the most relevant constraints on the Type-III 2HDM parameter space were taken into account.

## 4 Summary

This mini-review on lepton flavor violation discusses some general aspects of LFV, emphasizing those that can be used to get a hint on the underlying physics. In

<sup>†</sup>More complicated multi-Higgs models have been examined too [26, 27, 28, 29].

particular, the search for correlations and hierarchies among LFV observables have been shown to be useful tests in many scenarios. These patterns are not only possible, but expected features of general classes of models.

We have briefly reviewed two specific topics that illustrate this program. First, we have considered LFV in low-scale seesaw models, where the dominance of dipole operators gets broken due to the presence of light right-handed neutrinos. This leads to a richer phenomenology, with several observables with similar rates. Then we have discussed Higgs LFV decays, reviewing some proposals in the literature that fail to give observable rates at the LHC due to other flavor bounds. The most general 2HDM (the so-called Type-III version) can however lead to large  $h \rightarrow \ell_i \ell_j$  branching ratios, thus becoming the perfect scenario for Higgs induced flavor effects <sup>‡</sup>.

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<sup>‡</sup>We have refrained from discussing the recent  $2.5\sigma$  excess found by the CMS collaboration in the  $h \rightarrow \tau\mu$  channel [33]. This intriguing excess would translate into a largish  $\text{BR}(h \rightarrow \tau\mu) = (0.89^{+0.40}_{-0.37})\%$ , thus favoring an explanation based on the Type-III 2HDM [32].

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